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Limnological Responses to Changes in the Withdrawal Zone of Eau Galle Reservoir, Wisconsin

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PURPOSE: The purpose of this research was to demonstrate limnological responses to a change in reservoir discharge from a predominantly surface withdrawal in 1991 to a hypolimnetic withdrawal in 2003.

BACKGROUND: Control of reservoir discharge regime and flushing of different strata may be a viable means of improving water quality in Corps of Engineers reservoirs. For instance, a hypolimnetic withdrawal can be effective in removing internal phosphorus (P) loads from the system that would otherwise subsidize algal growth (Nürnberg 1987, Nürnberg et al. 1987). However, cold-water releases can also decrease thermal stability, making a reservoir more susceptible to mixing and vertical entrainment of nutrients, particularly from riverine interflows (Stauffer and Armstrong 1984, Gaugush 1984, Effler et al. 1986). In contrast, discharging primarily from the surface of a reservoir can result in strengthened thermal stability, reducing the potential for vertical entrainment of hypolimnetic nutrients for algal uptake. Increased flushing rates in the epilimnion may also be effective in removing algal populations from the system at a greater rate than their doubling time (Pridmore and McBride 1984, Soballe and Kimmel 1987).

The objective of this research was to compare limnological responses of a Corps reservoir to changes in its withdrawal regime from predominantly surface discharge to hypolimnetic discharge during the summer period in order to explore the possibility of using selective withdrawal as a rehabilitation technique for reducing nuisance algae. This information represents an extension of earlier work on the impacts of withdrawal operations on reservoir water quality (Barbiero et al. 1997).

SITE DESCRIPTION AND RESERVOIR OPERATIONS: Eau Galle Reservoir is a small (0.6 km^2) U.S. Army Corps of Engineers (St. Paul District) flood-control impoundment located in west-central Wisconsin. Its mean and maximum depths are 3.2 m and 9 m, respectively. The lake is eutrophic, exhibits high concentrations of P (0.092 mg/L) and chlorophyll (37.2 mg/m^3; Barko et al. 1990), and has a mean summer trophic state index for chlorophyll of 66 (Carlson 1977). The major tributary inflow, Eau Galle River, drains a predominantly agricultural (dairy farming, pasture, and forage and row crops) watershed (Ashby 1985). Discharges from the dam occur via an uncontrolled surface morning-glory structure located at 286.5 NVGD and a controlled hypolimnetic gate located 7.2 m below the surface morning-glory structure. Surface discharge typically occurs during storm inflow, while hypolimnetic releases dominate during periods of nominal inflow.

In 1991, the hypolimnetic discharge gate was completely closed between April and July to examine lake and discharge response to predominantly surface release. The hypolimnetic gate was opened in early August 1991 to discharge bottom water at a flow rate of ~ 0.4 cms (cubic meters per second). In 2003, the hypolimnetic gate was set to a discharge rate of ~ 0.4 cms throughout the summer. Storm inflows that caused an increase in pool elevation above the morning glory structure resulted in some surface discharge as well. Reservoir discharge operations in 2003 were being managed for maintenance of cold-water fisheries (trout) in the tailwater via hypolimnetic releases of cold water stored in the reservoir.

METHODS: Inflows from the Eau Galle River and discharge from the reservoir were determined using continuous stage monitors and relationships between stage and flow over various flow regimes. Pool elevation was measured using a continuous stage monitor. Hypolimnetic flows were calculated using engineering relationships between head and gate opening. Surface withdrawals were calculated as total discharge from the reservoir minus calculated hypolimnetic discharge. Samples for total P were collected at biweekly intervals or less at the inflow and discharge station. Total P was analyzed using automated colorimetric techniques (Technicon Autoanalyzer II in 1991 and Lachat QuikChem in 2003) following potassium persulfate digestion American Public Health Association (APHA) 1992). P loading to the reservoir during the summer period (June through September) was estimated using the software program *FLUX* (Walker 1996).

In-lake sampling was conducted at a deep (~8.7 m), centrally located station at weekly to biweekly intervals between June and September. Water temperature was measured in situ at 0.5- to 1-m intervals between the reservoir surface and bottom using a Hydrolab Surveyor II or III (Hach Company, Loveland, Colorado). Reservoir stability was calculated according to Idso (1973) as:

$$S = g / A \int_{0}^{z_m} (z - z_g)(\rho_z - \rho_g) dz \qquad 1)$$

where g is the acceleration due to gravity (m/s), A is the surface area (m^2), z_m is the maximum depth (m), z is the depth, z_g is the depth of the center of mass, p_z is the density of water (kg/m^3) at depth z, and p_g is density of water at z_g. The metalimnion was estimated as the region where the relative thermal resistance to mixing (RTRM) was 30 or greater (Kortmann et al.1982) according to the equation:

$$RTRM = (\rho_z - \rho_{z+1}) / (\rho_{5C} - \rho_{4C}) \qquad 2)$$

Water samples were collected at 1-m intervals during the summer for analysis of total P and chlorophyll. Chlorophyll was extracted in 90 percent acetone and corrected for phaeopigments with 1N hydrochloric acid in 1991 (APHA 1992). A 50:50 mixture of acetone and dimethylsulfoxide was used for chlorophyll extraction in 2003 and fluorometric analysis following procedures described in Welschmeyer (1994). Although data are compared for the two years of study, caution is used in interpretion due to differences in extraction methodology. Secchi disk transparency was measured using a 10-cm black and white alternating disk.

RESULTS: Storm inflows occurred periodically during both summer periods; mean daily flow was 0.9 cms in 1991 and slightly higher at 1.0 in 2003. Discharges from the reservoir were entirely from the surface morning-glory structure between June and late July 1991 (Figure 1). A large storm inflow resulted in elevated surface discharge in June 1991. However, during most of the summer period of 1991 discharges were nominal. Between late July and September 1991, greater than 60 percent of the discharge from the reservoir came from the hypolimnion in conjunction with the opening of the bottom gate. Storm inflows in September 1991 resulted in significant discharge of

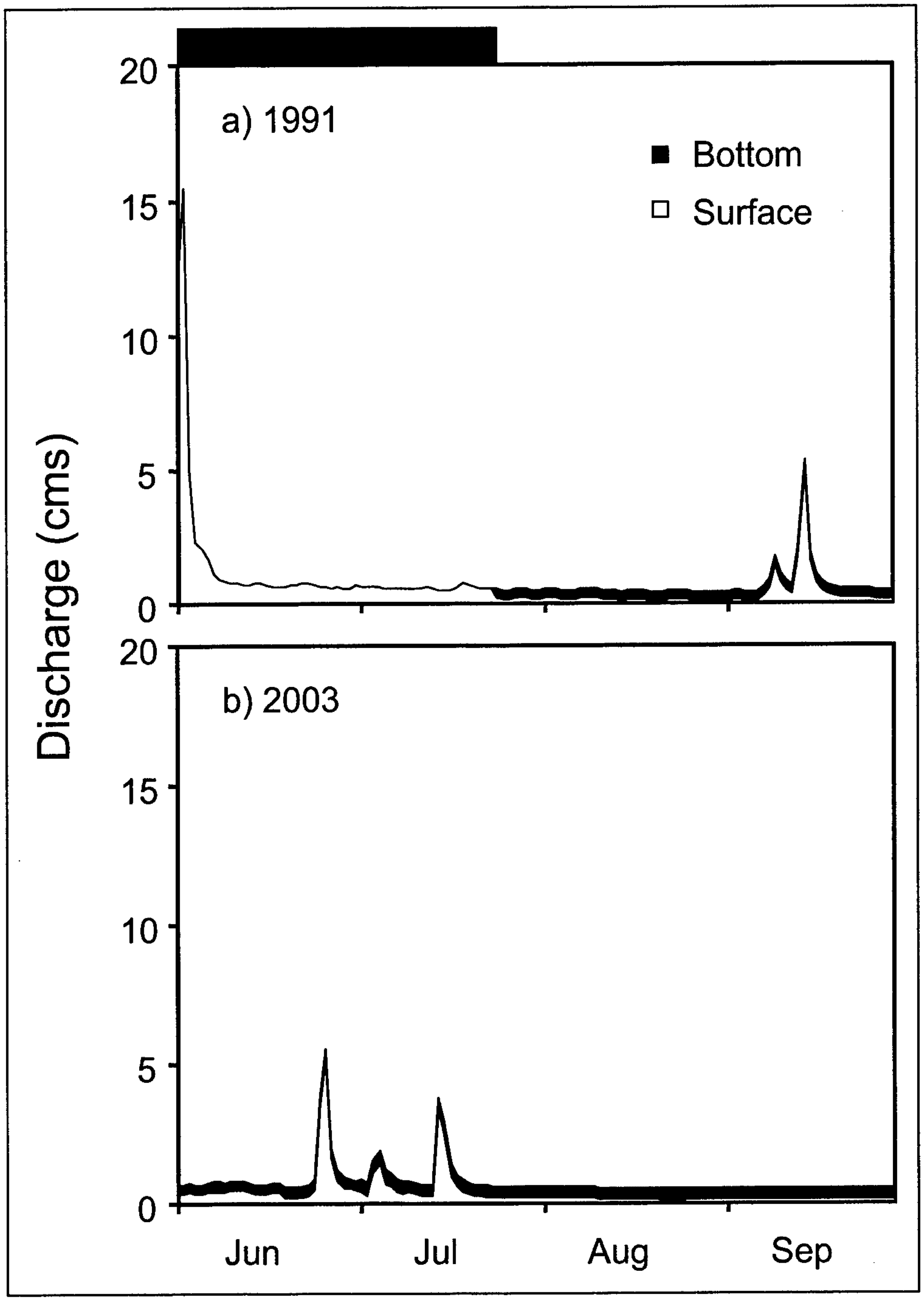

Figure 1. Seasonal variations in surface and bottom discharge from Eau Galle Reservoir in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

surface water from the reservoir. Tailwater temperatures were elevated during the period of predominantly surface withdrawal in 1991, indicating discharge of warmer surface water in the lake (Figure 2). Initiation of hypolimnetic releases in late July of 1991 resulted in a marked decline in tailwater temperatures. In 2003, greater than 60 percent of the discharge came from the bottom withdrawal structure during all periods of nominal flow (Figure 1). Storms in June and early July 2003 resulted in predominantly surface discharge during pool elevation rises. During 2003, hypolimnetic releases of cooler water resulted in tailwater temperatures ranging between 15 °C and 25 °C (Figure 2), similar to temperature ranges observed during the period of hypolimnetic discharge in 1991.

As a result of surface withdrawal in 1991, the reservoir developed strong stratification with a shallow epilimnion and a well-defined metalimnion located between the ~ 1-m and 5-m depths (Figure 3). Opening of the hypolimnetic gate in late July 1991 led to discharge of cooler bottom

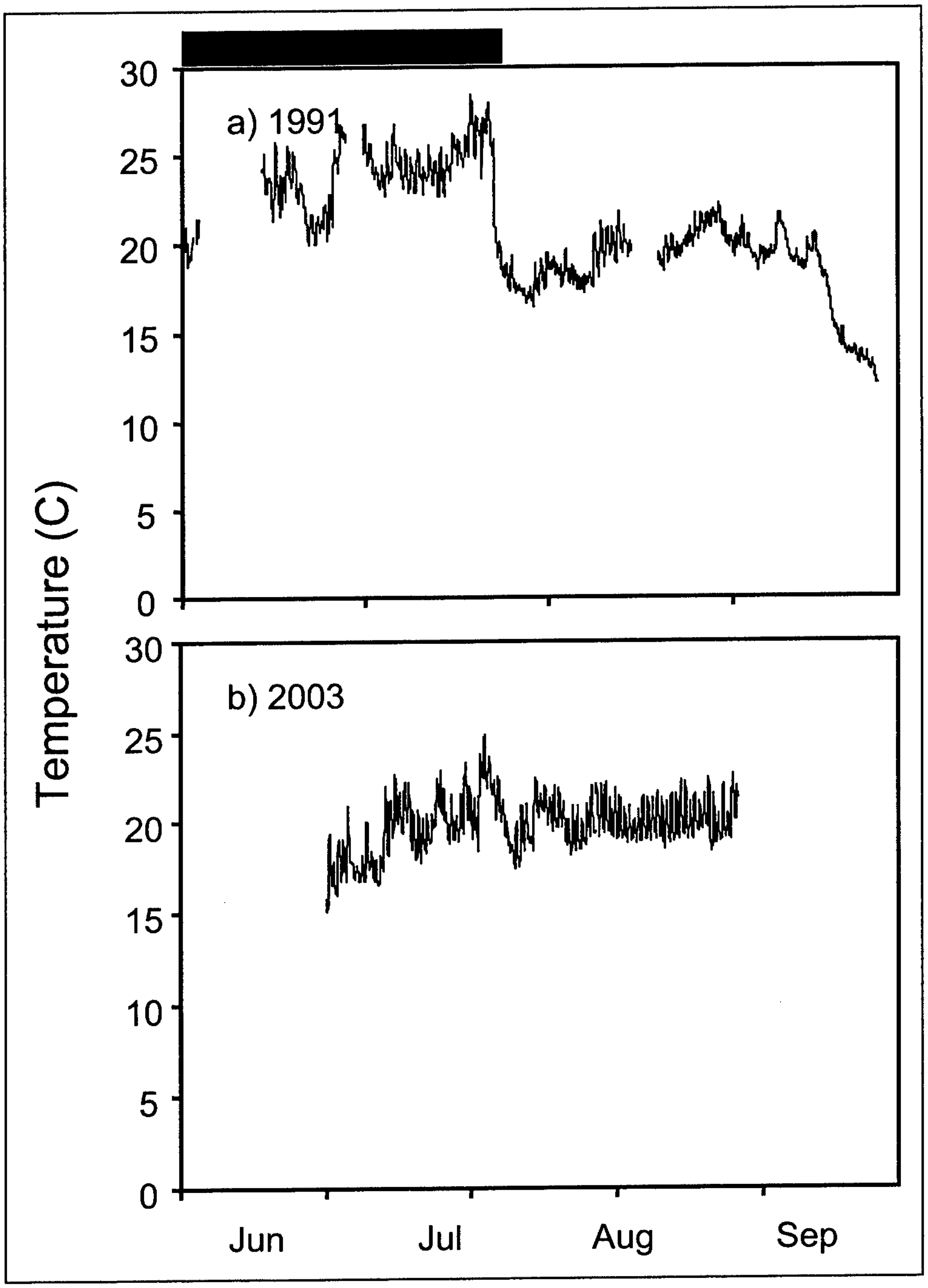

Figure 2. Seasonal variations in Eau Galle Reservoir tailwater temperatures in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

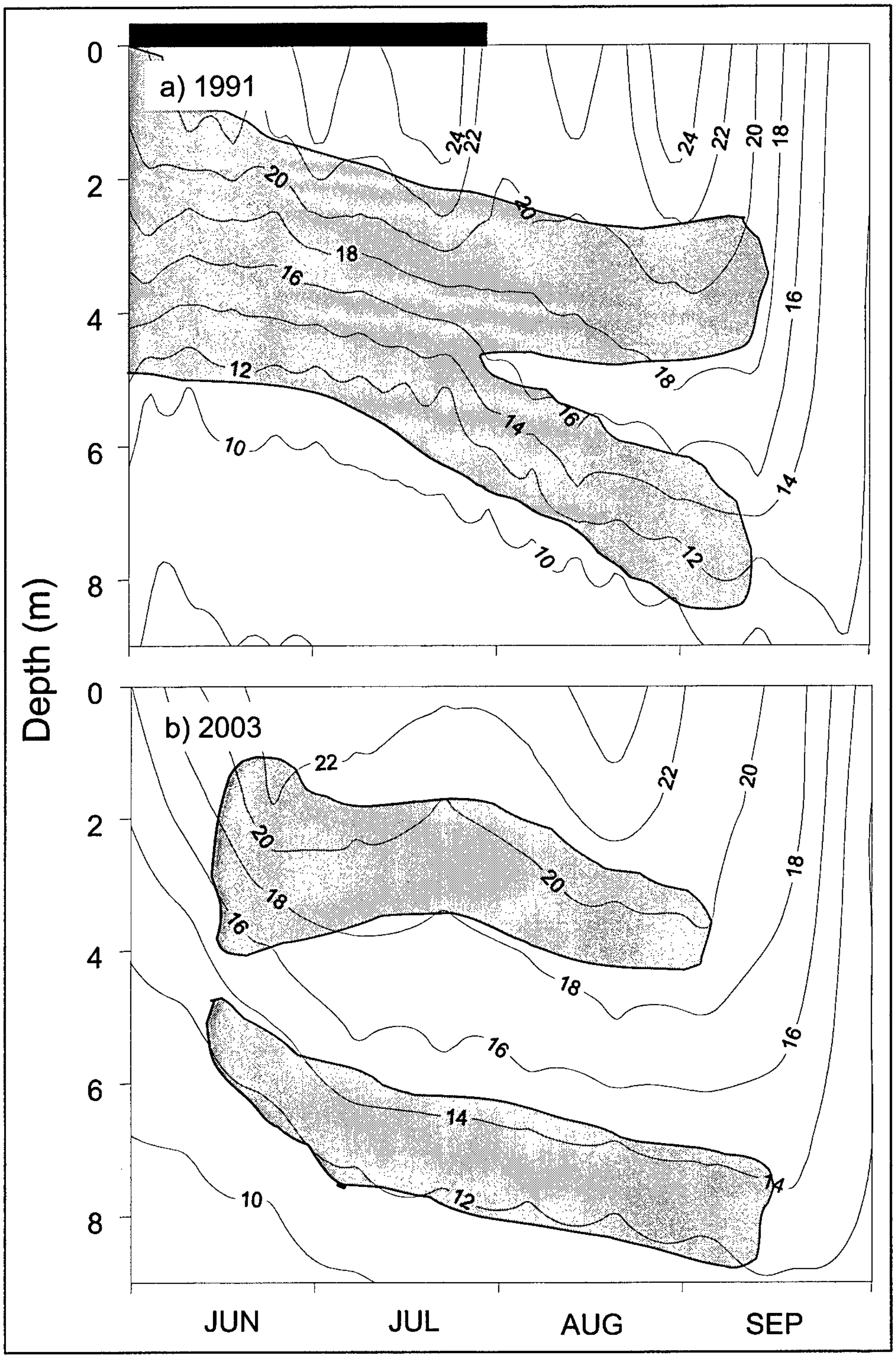

Figure 3. Contours of water temperature (°C) in Eau Galle Reservoir in 1991 and 2003. Gray shaded areas represent the location of the metalimnion. Black bar denotes the period of exclusive surface discharge in 1991

water from the reservoir that was replaced by warmer riverine water, resulting in a weakening of thermal stratification and a split in the metalimnion at the ~ 5- to 6-m depth. In 2003, continuous hypolimnetic withdrawal resulted in the development of two metalimnetic regions; one located at the ~2-m depth and one at the ~6-m depth (Figure 3).

Thermal stability generally exceeded $60 \cdot 10^6$ kg m^{-2} s^{-2} during the period of surface withdrawal in 1991 (Figure 4), but declined in conjunction with discharge of hypolimnetic water in late July. In 2003, stability was generally less than $60 \cdot 10^6$ kg m^{-2} s^{-2} throughout the summer period. Overall, mean thermal stability during the periods of surface withdrawal between June and July 1991 was significantly higher ($p<0.05$; SAS 1994) than mean stability observed during the same period in 2003 (Table 1).

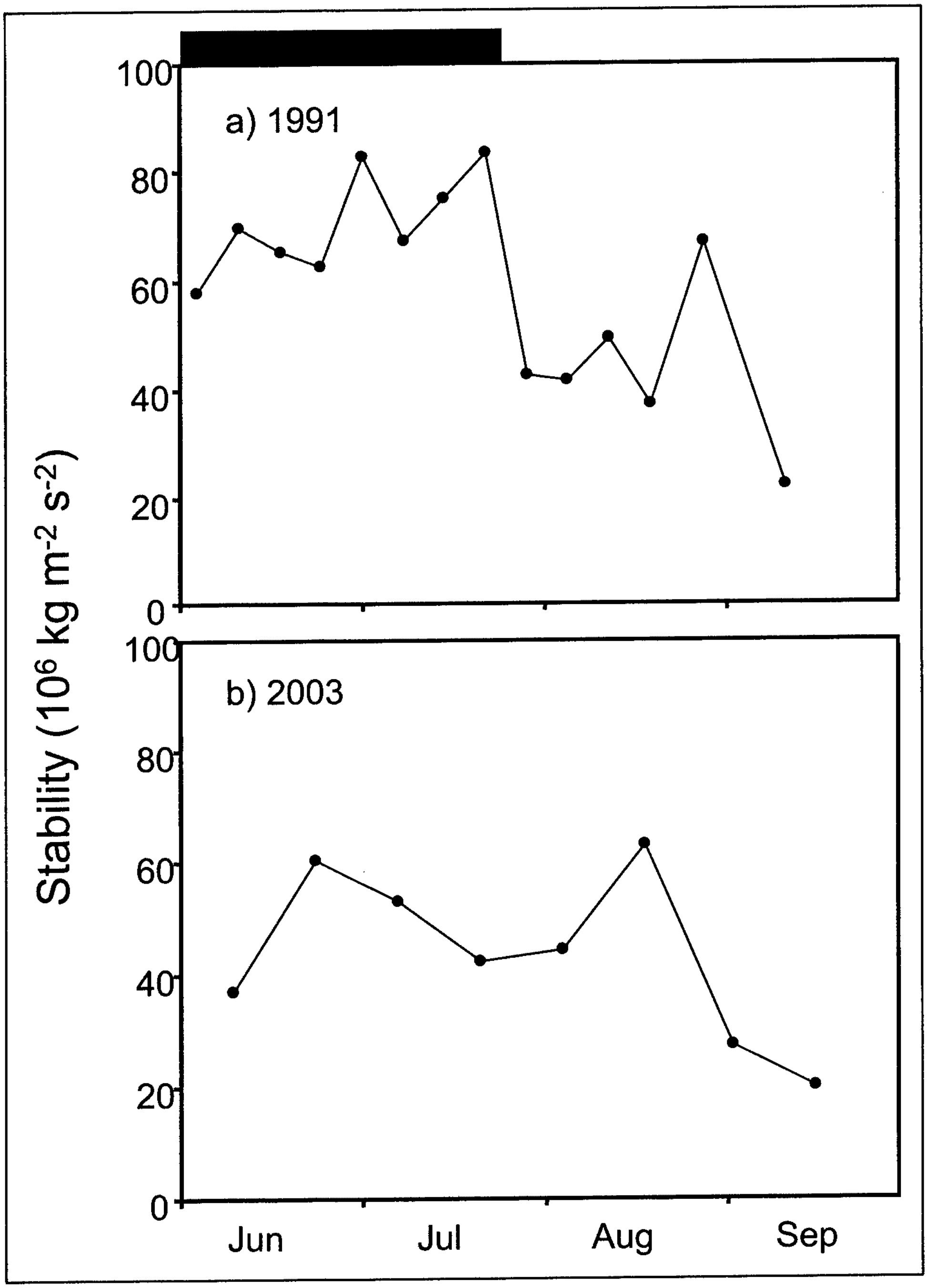

Figure 4. Seasonal variations in reservoir stability in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

Table 1
Comparison of Mean (1 Standard Error in parentheses) Physical, Chemical, and Biological Properties for the Period June Through Late July, 1991 and 2003[1]

Variable	1991	2003
Stability (10^6 kg m^{-2} s^{-2})	67.5 (4.6)*	47.5 (4.1)*
Epilimnetic residence time (days)	9.5 (0.6)*	16.2 (1.0)*
Surface chlorophyll (mg m^{-3})	21.5 (4.3)*	46.2 (9.9)*
Integrated chlorophyll (mg m^{-3})	31.1 (2.4)	39.5 (4.5)
Secchi transparency (m)	1.2 (0.1)*	0.6 (0.1)*
Epilimnetic total phosphorus (mg L^{-1})	0.059 (0.012)	0.069 (0.013)
Hypolimnetic total phosphorus accumulation (kg d^{-1})	1.9	2.0

[1] Surface withdrawal occurred during those months in 1991 while hypolimnetic and surface withdrawal occurred during those same months in 2003. Asterisks indicate significant differences in the mean at the 5% level or less (t-test; Statistical Analysis System (SAS) 1994).

In 1991, epilimnetic hydraulic residence time of the upper 1-m water column was less than ~ 10 days during the period of surface withdrawal and increased markedly from late July through September during the period of hypolimnetic discharge (Figure 5). In 2003, storm inflows and discharge through the surface morning-glory structure in June and early July reduced the epilimnetic hydraulic residence time to less than 10 days. However, during periods of nominal flow and predominantly hypolimnetic release between mid-July and September, the epilimnetic residence time increased substantially. Mean (between June and July) epilimnetic hydraulic residence time was significantly lower in 1991 than in 2003 (Table 1).

Variations in withdrawal characteristics did not appear to have an effect on total P concentrations in the epilimnion or accumulation of total P in the hypolimnion, as there were no significant differences in means between the two years of study (Table 1). Mean total P concentrations were also relatively high in the epilimnion during both years, reflecting eutrophic conditions. Peaks in concentration during the summer of both years coincided with the occurrence of storm inflows (not shown), suggesting that external P loading from the Eau Galle River most likely regulated total P concentrations during both summers. External total P loading was slightly higher in the summer of 1991 (20.7 kg d^{-1} ± 4.1 Standard Deviation; SD) versus 2003 (15.9 kg d^{-1} ± 3.2 SD) and the flow-weighted concentration ranged between 0.21 and 0.23 mg L^{-1}.

Chlorophyll concentrations in the upper 5 m of the water column exhibited a peak in June 1991, then declined in the surface waters between late June and September (Figure 6). However, peaks in chlorophyll concentration were observed in the metalimnion of the reservoir between June and September 1991. In 2003, a completely opposite vertical distributional pattern occurred. Chlorophyll concentrations were highest in the surface waters and decreased with increasing depth. Although mean water column concentrations in the upper 4 m were statistically similar for both years (31 mg/m^3 in 1991 versus 39 mg/m^3 in 2003), mean surface (i.e., upper 0.5 m) chlorophyll was significantly lower in 1991 than in 2003 (Table 1).

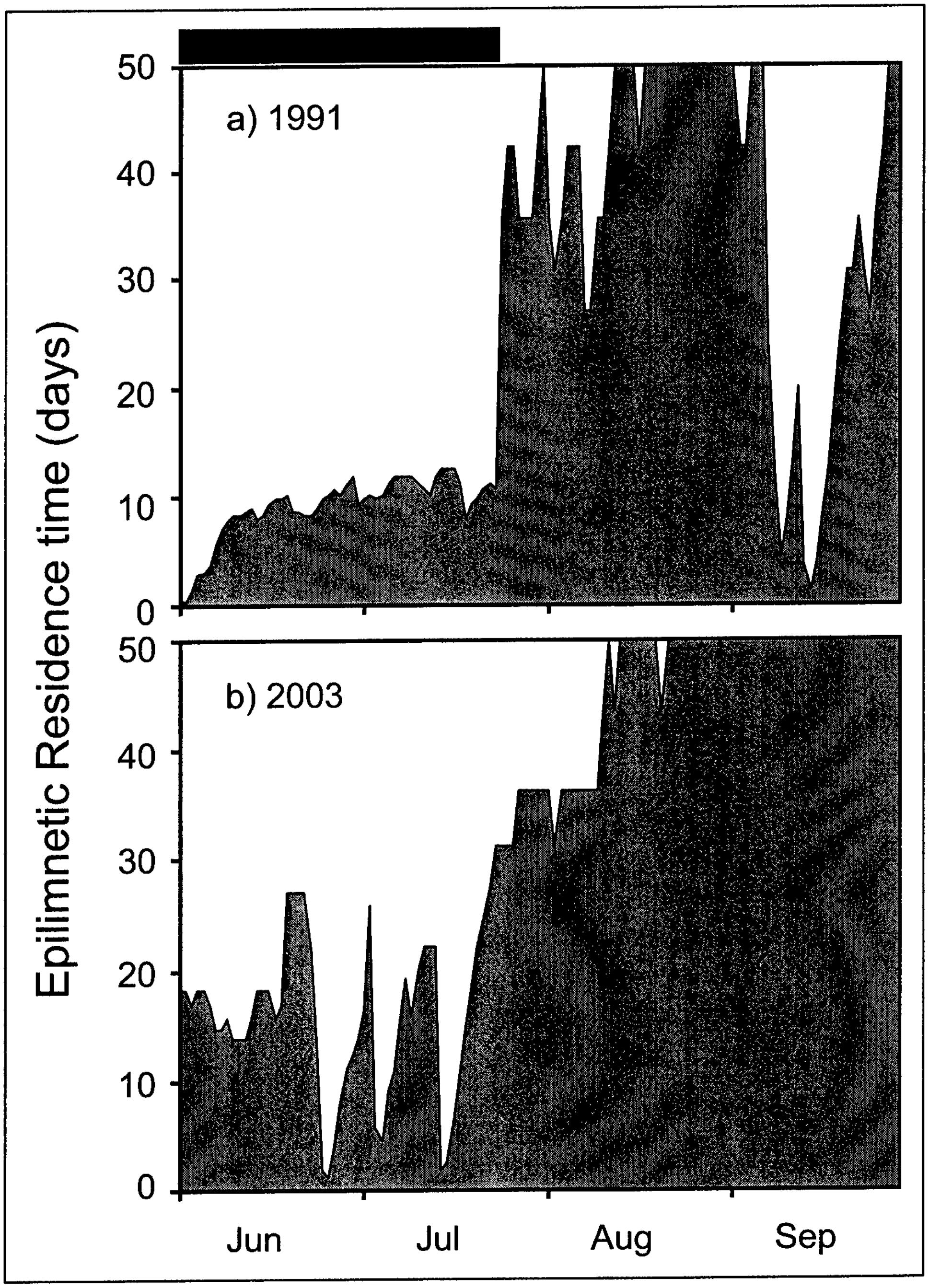

Figure 5. Seasonal variations in the residence time of the upper 1 m (shaded area) of the epilimnion of Eau Galle Reservoir in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

Secchi transparency increased above 1 m in late June 1991, and was greater than 2 m for much of August, coinciding with lower chlorophyll in the surface waters (Figure 7). In 2003, Secchi transparency was nearly constant at less than 1 m. Overall, mean Secchi transparency was significantly greater in 1991 than in 2003.

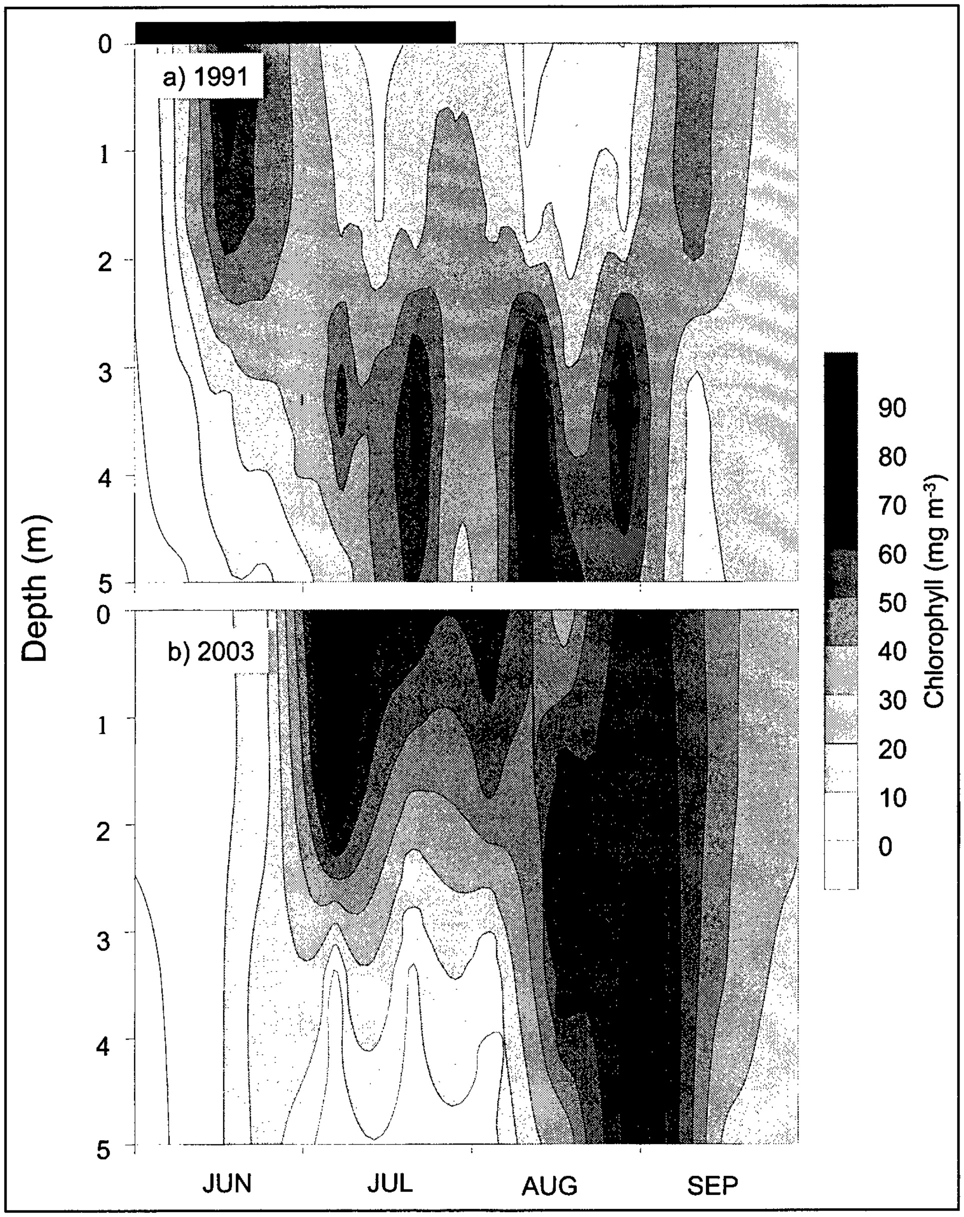

Figure 6. Contours of the vertical distribution of chlorophyll in the upper 5-m water column (note depth axis) of Eau Galle Reservoir in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

DISCUSSION: The most striking responses to differences in withdrawal were changes in the thermal structure of the reservoir. Under conditions of predominantly surface releases in 1991, thermal stratification was stronger (i.e., greater stability) with the occurrence of a shallower epilimnion and larger metalimnion and cooler temperatures in the hypolimnion. Hypolimnetic withdrawal in 2003 resulted in the continual removal of cooler bottom water and replacement with warmer water originating from the Eau Galle River, causing a weakening of thermal gradients and stability and the development of multiple metalimnions. Changeover to hypolimnetic releases in early August of 1991 was also accompanied by the establishment of a weak metalimnion in the upper waters and one immediately below the hypolimnetic discharge structure.

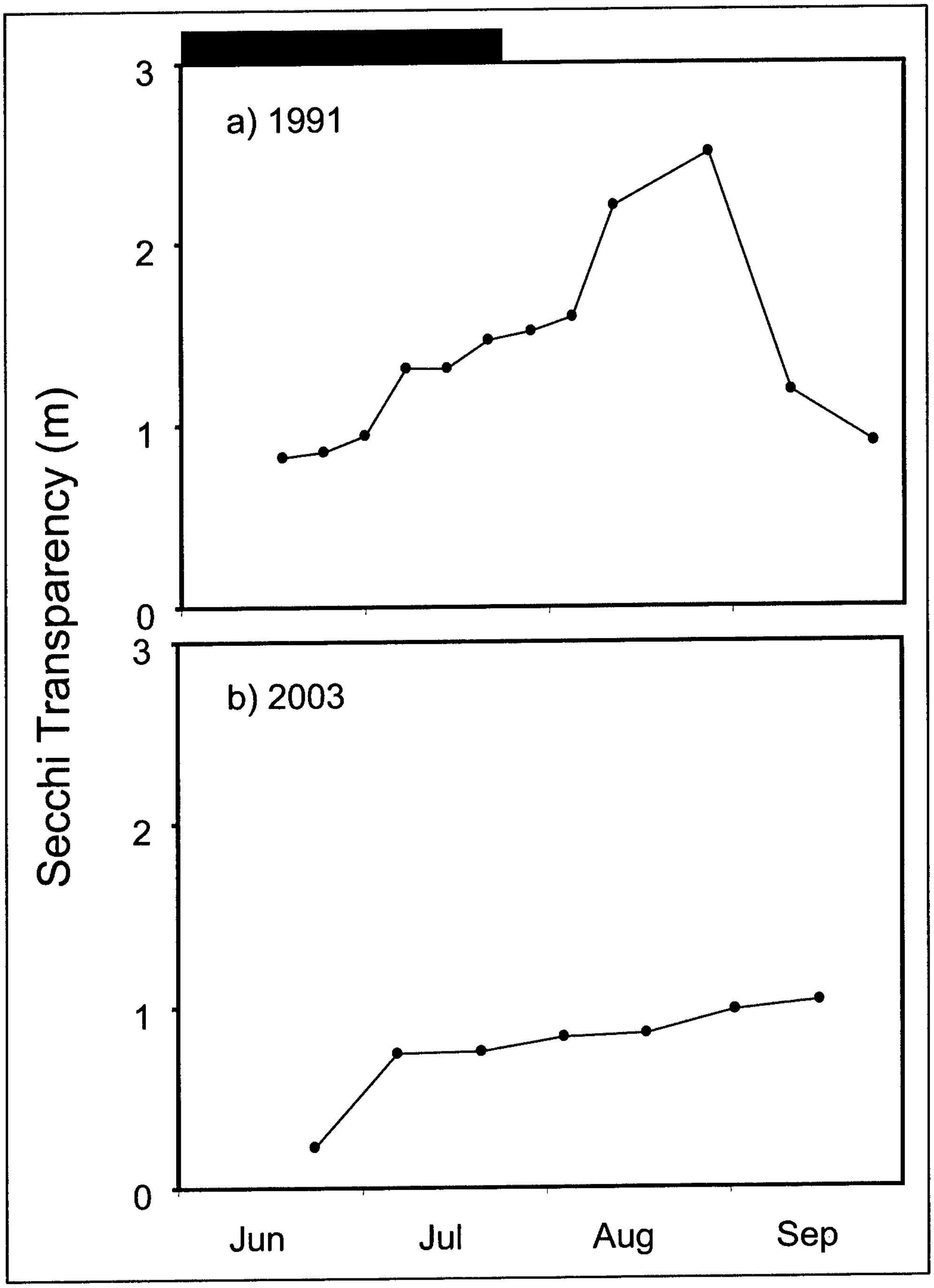

Figure 7. Seasonal variations in Secchi transparency in Eau Galle Reservoir in 1991 and 2003. Black bar denotes the period of exclusive surface discharge in 1991

While storm inflows impacted total P concentrations and concentrations were similar in the epilimnion during both years, there appeared to be a marked change in the vertical distribution of chlorophyll, which coincided with differences in the withdrawal regime. During both years, overall chlorophyll concentrations in the upper 4-m water column were similar. However, chlorophyll was concentrated near the base of the epilimnion in 1991 versus 2003, when it was concentrated near the surface of the lake. While P was probably not limiting to algal growth during either year, the epilimnetic residence time was much lower in 1991 than in 2003, suggesting possible impacts on the distribution of algae. Barbiero et al. (1997) also found that the algal assemblage was dominated by *Fragilaria crotonensis* in 1991 versus other years when the reservoir is typically dominated by nuisance cynapohytes (blue-green bacteria) and dinoflagellates (*Ceratium hirundinella*).

Higher flushing in the epilimnion could impact algal communities by cell removal from the system at rates which are greater than algae doubling times (Taylor et al. 1988). For instance, Van Nieuwenhuyse and Jones (1996) found low chlorophyll:total phosphorus coefficients for riverine systems and suggested this pattern was due to greater flushing of chlorophyll in these systems even though P concentrations were sufficient to sustain high productivity. In addition, Walker (1996) suggested that under conditions of high nutrient turnover times and low residence times, chlorophyll production may not be in equilibrium with nutrient levels in the water column. In Eau Galle Reservoir, surface withdrawal during 1991 most likely impacted the upper 1 m or less and flushing rates approaching 0.2 d^{-1} could have resulted in some cellular removal in excess of doubling times, particularly for blue-green bacterial biomass, which typically reside near the surface. However, Barbiero et al. (1997) found only weak relationships between flushing and blue-green bacterial dominance for Eau Galle Reservoir and suggested that higher temperatures (i.e., > 20 °C) could also explain differences in the dominance of this nuisance algal group. They also noted that significant cellular flushing and reductions in algal biomass were apparent primarily during storm inflows, which occurred during both years.

The results of this study suggest that biological responses to a changeover in withdrawal regime were complex in this reservoir and not readily explainable in terms of nutrient dynamics or hydrology versus the more predictable changes that occurred in the thermal structure of the lake. The year 1991 remains unusual in that a diatom population dominated the algal assemblage for most of the summer in conjunction with surface discharge, a phenomenon that was not observed in 14 years of study on Eau Galle Reservoir (Barko et al. 1990). Its residence in the upper metalimnion resulted in markedly improved Secchi transparency and low turbidity in the surface waters throughout the summer of 1991. Attempts to maintain surface withdrawal in other years (i.e., 1992 and 1993) were confounded by unusual weather patterns (unusually cold air temperatures in 1992 and record precipitation in 1993) and improved Secchi transparency and lower surface chlorophyll were not observed during those years. Clearly, other factors such as reductions in external P loading need to be considered in conjunction with discharge management in order to improve water quality in this system.

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